MICRO MAGNETIC INDUCTION MACHINES FOR PORTABLE POWER APPLICATIONS

Florent Cros, David P. Arnold, and Mark G. Allen
ECE Department, Georgia Institute of Technology
Atlanta, GA 30332

and

Sauparna Das, Hur Koser and Jeffrey H. Lang
EECS Department, Massachusetts Institute of Technology,
Cambridge, MA 02139

ABSTRACT

This paper[1] presents recent advances in the development of a micro magnetic induction motor/generator. The development of this machine is part of an ongoing project to develop high-power-density electric machinery for use in portable power applications. The results reported here focus on testing a first-generation non-laminated tethered motor, and fabricating a second-generation laminated tethered motor. These tethered motors are metrology devices designed for exploring and characterizing the fabrication and operating behavior of the micro magnetic induction machine.

INTRODUCTION

The MIT Gas Turbine Engine Project [1] seeks to develop a millimeter-scale gas turbine engine generator that can produce tens of Watts of electrical power for portable general-purpose use. As part of that project, several induction generators are under development as the electromechanical energy converter. The baseline generator is an electric induction generator [2], chosen for its compatibility with the MEMS-based fabrication of the rest of the system. However, in parallel with its development we are also developing a magnetic induction generator. It is the latter generator that is the subject of this paper. There are several reasons for our interest in the magnetic induction generator, which can also be used as a motor. First, as the torque and power targets for electromechanical energy conversion increase, so too will the size of the machines that perform the conversion. This increase is already sufficient for magnetic machines to be favored generally over electric machines in terms of torque and power density. Second, magnetic induction machines can operate with rotor-stator gaps much larger than is electromechanically feasible for electric induction machines. This results in greatly reduced windage losses, which leads to much greater system efficiency, all else being equal. Third, magnetic machines are inherently low-voltage high-current low-frequency machines by comparison. They are therefore better matched to their end use in the portable power applications of interest, and their power electronics should be much more compact and efficient. Thus, it is important to develop magnetic induction machines as alternatives to electric induction machines.

The development of micro magnetic induction machines for the applications described in [1] poses many challenges. First, the induction machines are fabricated primarily from thick magnetic cores of NiFe, and thick Cu conductors, for example. This must be integrated with the silicon-based fabrication of the turbomachinery with which the machines cooperate. The introduction of the cores and conductors into the high-temperature applications described in [1] also poses materials and thermal management challenges. Second, eddy currents in the magnetic cores can result in greatly reduced torque and power, and can also lead to significant losses. Thus, eddy currents must be managed through materials selection and/or development, and through core lamination. The work reported here directly addresses these challenges.

A solid model of our micro magnetic induction machine is shown in Figure 1. The machine is planar, with an axial air gap between the rotor and stator. The rotor is a solid magnetic disk that supports a highly conducting layer at the air gap. The annular stator core is slotted, and two coils are wound through its slots in spatial quadrature. The coils are fabricated in separate layers, and their end turns are exaggerated for improved heat transfer to the substrate.

[1] Prepared through collaborative participation in the Power and Energy Consortium sponsored by the U. S. Army Research Laboratory under the Collaborative Technology Alliance Program, Cooperative Agreement DAAD19-01-2-0010. The U. S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation thereon.

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**

4. TITLE AND SUBTITLE **Micro Magnetic Induction Machines for Portable Power Applications**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Georgia Institute of Technology,School of Electrical and Computer Engineering,Atlanta,GA,30332**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

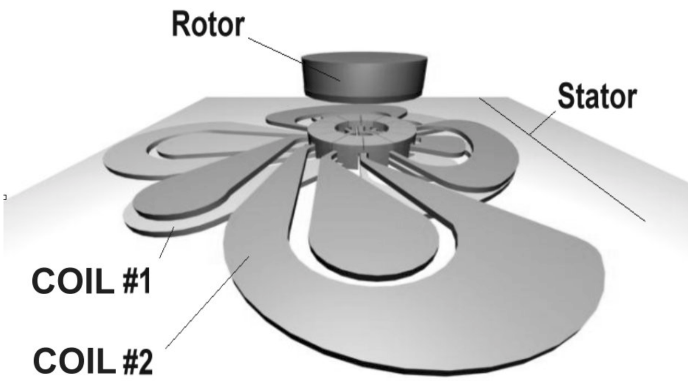

Figure 1. A solid model of the micro magnetic induction machine.

With its coils excited in temporal quadrature, the stator supports a traveling wave of current which excites a traveling air-gap magnetic field. This field in turn induces currents in the rotor conductor with which it interacts to produce a torque on the rotor. Such operation can lead to both motoring and generating power output. The machine shown in Figure 1 is an 8-pole machine having 4 slots per pole pair.

Figure 2 shows a micrograph of a fabricated stator having the same design. For photography purposes, the insulation that encloses the coils has been partially etched back to expose one coil. Figure 3 shows a close-up micrograph of the inner end turns. Both coils are visible in this figure. The machine shown in Figures 2 and 3 is fabricated with NiFe cores and Cu conductors; epoxy is used to insulate the Cu coils from one another and from the core.

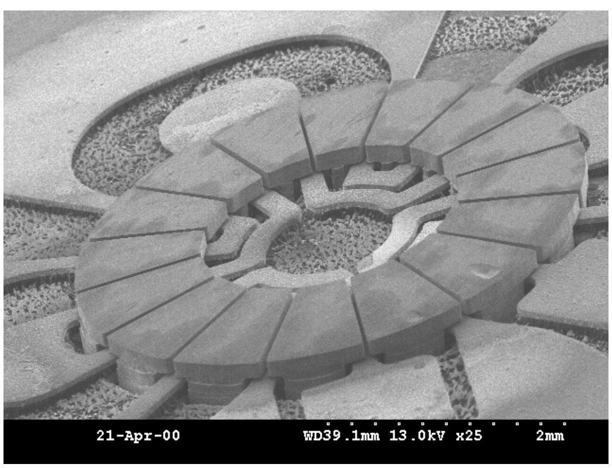

Figure 2. A micrograph of a first-generation non-laminated stator. The coil insulation has been partially etched back to reveal the coils

The motor is fabricated on a 1-mm-thick NiFe wafer. The inner and outer diameters of the stator core are 2 mm and 4 mm, respectively. The vertical NiFe slots are 250 µm tall. The copper coils are both 200 µm wide in the slots and 85 µm thick. The insulation separating the coils from one another and from the core is approximately 25 µm thick.

The rotor, which is not shown in the figures, is 4 mm in diameter and 500 µm thick, and its Cu layer is 8 µm thick. The typical rotor-stator air gap is 25 µm. Further fabrication and performance details can be found in [3,4,5,6,7]. Note that the machine shown in Figures 1 and 2 is not laminated for ease of initial fabrication. However, since it is designed to operate at electrical frequencies of 10 kHz to 200 kHz, its electromechanical performance will suffer significantly due to the presence of eddy currents and associated saturation, primarily in the stator core. The purpose of the work reported here is to address these effects, first by experimentally measuring and analytically modeling them, and then by developing a laminated stator to minimize their impact on performance.

TETHERED MOTOR CHARACTERIZATION

To investigate and characterize the fabrication and operation of the magnetic induction machine, we have designed and fabricated a tethered motor.

A tethered motor is one in which the rotor is suspended above the stator by axially stiff springs, or tethers. The tethers are flexible in the plane of the rotor allowing the rotor to rotate. The torque produced by such a motor is directly measurable through the bending of its tethers, which is easily calibrated through controlled excitation. Because the rotor is tethered, and hence stationary, the torque measurements are not obscured by bearing behavior, and are therefore very accurate.

The axial force of attraction between the rotor and stator may also be measured in this way. Thus, the tethered motor is the primary device with which we accurately measure the torque produced by a magnetic induction machine, and with which we experimentally validate our models of its behavior. Further, it is also an ideal machine on which to develop the fabrication of magnetic induction machines.

Following the methods outlined in [4,6] the torque produced by the tethered motor has been measured as a function of the amplitude and frequency of the currents in the stator coils. The results are shown as data points in Figure 4. The peak torque near 0.3 µNm at 6 A and 90 kHz is approximately a factor of 30 below what would be expected in the absence of stator eddy currents [3,6], and so these eddy currents do have a significant impact on performance. These eddy currents act to exclude magnetic flux from the stator core, and hence directly reduce the torque produced by the motor.

Following the methods outlined in [5,6], the models presented in [3,6] have been extended to include the

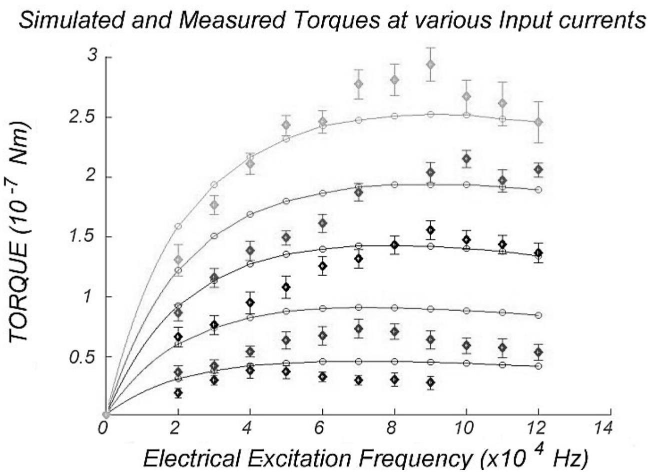

Figure 3. Experimentally measured torque (data points) is shown as a function of electrical excitation frequency for various values of peak stator current. Model predictions (solid lines) are also shown

effects of eddy currents in the stator and rotor cores. The nonlinear magnetization of the stator and rotor cores is also included. This extension is based upon a two-dimensional finite-difference time-domain simulation of magnetic diffusion in the stator core. The torques predicted by the extended model are shown in Figure 4 with solid curves. The good match between the experimental and modeled torque is further indication of the importance of eddy currents. The models further indicate that nearly all of the torque predicted in the absence of eddy currents can be recovered if the stator is laminated to a thickness on the order of 20 to 50 µm, depending upon operating conditions. For this reason, we are working towards laminating the stator at this length scale. Laminating the rotor does not appear to be important because it operates at a much lower electromagnetic frequency.

VERTICALLY LAMINATED INDUCTION MACHINE

In macro-scale magnetic devices, low-loss laminated cores are typically achieved by stacking alternating layers of core material and insulating material (which blocks eddy current flow), and laminating the entire stack together. Laminations have also been utilized in micromachined magnetic components. Previous approaches to micromachined laminations include one-step electroplating of vertical high-aspect-ratio NiFe structures [8]; repeated deposition of insulator, seed layer, and NiFe films [9]; multiple sputtering of thin magnetic and dielectric layers [10]; and mechanical lamination of polymer-coated NiFe foils [11].

Although these approaches have demonstrated improvement in device performance, processability and scaling remain as unaddressed issues. As permeabilities and desired operation frequencies increase, lamination thicknesses should be reduced to the micron to tens of microns range (i.e., on the order of the magnetic skin depth, which depends on the frequency) while simultaneously maintaining total core thicknesses of tens to hundreds of microns to prevent saturation. These requirements dictate large numbers of thin, high-aspect-ratio laminations, which are difficult to achieve using the previously-proposed approaches. For example, in the case of vertically-laminated structures, the required aspect ratio of the mold laminations increases, making mold fabrication difficult. Horizontal lamination using repeated deposition of magnetic thin films and insulators, e.g., by sequential sputtering, overcomes this difficulty but may not be able to achieve the required overall stack thicknesses due to stress issues. Electroplating of horizontal laminations offers the possibility of fabricating structures of sufficient overall thickness, but the repeated switching of substrates between plating bath and vacuum system as detailed in [3] becomes unmanageable as the number of layers increases. Finally, conventional foil lamination becomes difficult and impractical as the foil thickness approaches the micron range, especially since mechanical strain of magnetic foils has been demonstrated to degrade magnetic properties.

When correctly laminated, the ferromagnetic core structure of the stator is formed of successive concentric vertical blades. A three-dimensional schematic view of the complete structure is presented in Figure 4. We endeavored to fabricate a second generation of functional two-coil stators that include NiFe laminations of various thicknesses. We altered the fabrication method that we previously developed for the non-laminated micro-induction machine. Lamination widths range from 25 to 100 µm. The overall height of the magnetic structure is set by the thickness of all the metal layers combined, i.e. the coils and the electrical passivation layers. Because of the challenge associated with the fabrication of vertically-stacked multilayer high aspect ratio structures, we decided to limit the overall thickness of the complete laminated structure for initial fabrication trials. This translates directly into fabricating Cu coils in which the thickness is less than the thickness of the coils of the first generation of non-laminated stators. As a consequence, these Cu coils have a lower maximum current safety threshold. Even though materials and maximum achievable dimensions will limit these devices to relatively low operating currents (less than 6A RMS), such laminated stators are essential parts of the development plan since they will allow us to collect important data on performance of optimized magnetic structures.

The fabrication starts with electrodepositing a NiFe laminated "back-iron" plate (not shown). This structure is passivated using 10 µm thick photosentitive SU-8 epoxy layer (not shown). A first Cu coil is electrodeposited (from a removable mold of thick commercial photoresist: 40 µm), and a thick layer of photodefined SU-8 is deposited on top of the metal lines (Figure 5.1). Due to the excellent planarization properties of SU-8, a conventional UV photolithography step is performed to create high aspect ratio trenches and walls (Figure 5.2 and 5.3). The trenches are subsequently filled with electroplated NiFe, completing one metal layer (Figure 5.4). The operation is repeated in order to complete the second metal layer. Once the metal layers are fabricated, a final NiFe electroplating sequence completes the structure. Ten masks and photolithography steps are needed to produce a functional device.

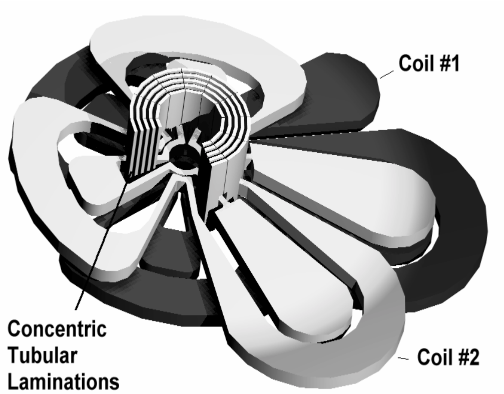

Figure 4. 3D artistic view of a 2-coil stator with fully laminated NiFe core.

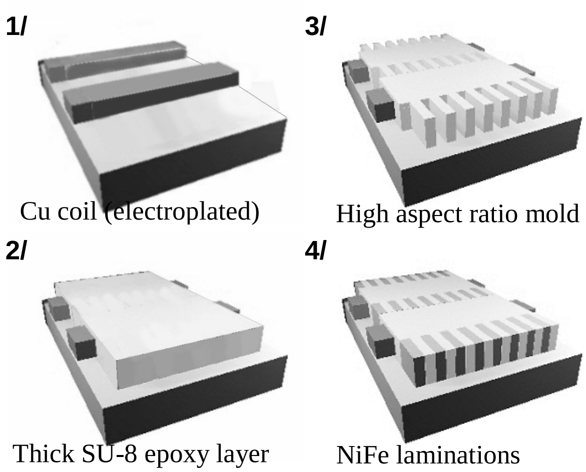

Figure 5. Complete fabrication sequence for one metal layer of a 2-coil stator with laminated NiFe core

A 3D view of a complete multilayer structure is depicted in Figure 6. The following table (Table 1) introduces important traits and geometrical figures of the fabricated stators. We fabricated the devices using various substrates such as NiFe (80%-20%) wafers, high electrical resistivity ferrite wafers, and RF compatible ceramic boards. Examples of functional devices are presented Figures 7 and 8. These devices are currently under test.

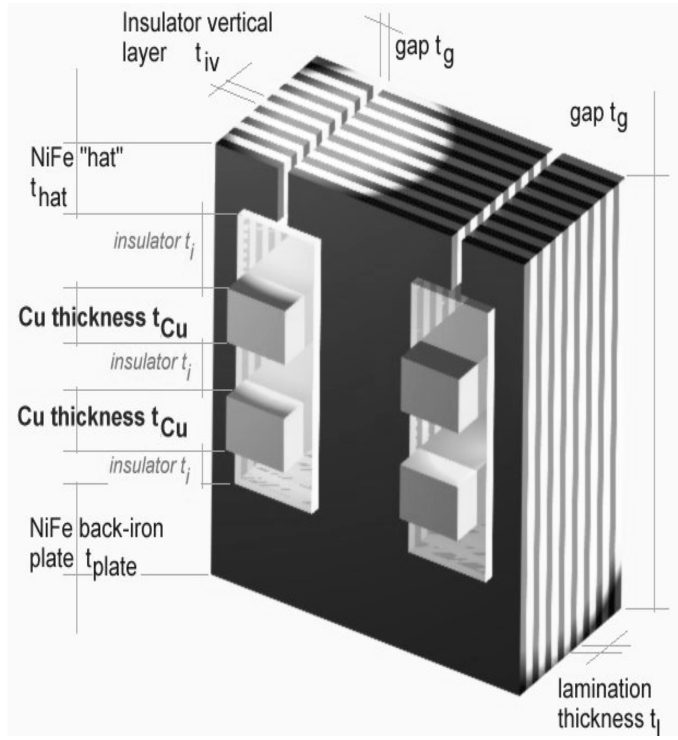

Figure 6. 3D artistic view of a functional 2-coil stator with laminated NiFe core.

Cu coil thickness	t_{Cu}	35 µm
Number of coils		2
NiFe back-iron plate (thickness)	t_{plate}	60 µm
NiFe "hats" thickness	t_{hat}	60 µm
Insulator thickness	t_i	10 µm
Vertical lamination width	t_l	25-100 µm
Vertical insulating material	t_{iv}	25-50 µm
Gap between NiFe slots	t_g	10 µm
Max. current before destruction		6 A (RMS)
Overall thickness (not including the wafer)		>250 µm
Substrate: NiFe, Ferrite, RF ceramic board		

Table 1. Important traits and geometrical figures of fabricated stators with NiFe laminated core

Figure 7: Optical photography of a complete stator with laminated NiFe core. The device is built on top of a 5 mm thick ferrite wafer.

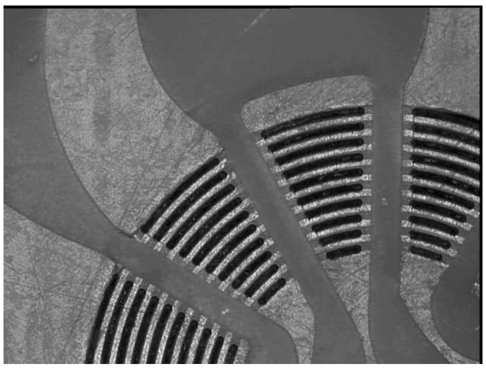

Figure 8: Optical photograph of a laminated stator before completion (detail). The darker regions indicate the presence of electroplated concentric NiFe vertical laminations (witdh: 50 µm)

SUMMARY & CONCLUSIONS[2]

During the past year, our development of a micro magnetic induction machine for portable power applications has focused on understanding and minimizing the effects of eddy currents in the machine. Specifically, we have extended our models of machine performance to include the effects of eddy currents and the magnetic saturation that they cause. The models explain the measured performance of the machine very well. These models also predict the degree to which the machine must be laminated in order to minimize the negative impact of eddy currents. Finally, we have demonstrated the ability to fabricate magnetic induction machines with this desired degree of lamination. Testing of the laminated machines is now underway.

[2] The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Laboratory or the U.S. Government.

ACKNOWLEDGMENTS

This work was supported by the Army Research Office under contract DAAG55-98-1-0292 managed by Dr. T. L. Doligalski, and a contract from the Army Research Laboratory managed by Mr. J. Hopkins. This work is based on part of [6,7].

REFERENCES

[1] AH Epstein, et al, "Power MEMS and Microengines", IEEE, Conference on Solid State and Actuators, 1997.

[2] C. Livermore, A. Forte, T. Lyszczarz, S. Umans, and JH. Lang, "Electric Induction Motor/Generators for Portable Power Applications", submit. CTA review.

[3] H Koser and JH Lang, "Modeling A High Power Density MEMS, Magnetic Induction Machine", International Conference on Modeling and Simulation of Microsystems, 286-289, Hilton Head, SC, 2001.

[4] H Koser, F Cros, MG Allen and JH Lang, "A High-Torque Density MEMS Magnetic Induction Motor", International Conference on Solid-State Sensors and Actuators, Munich, Germany, June 2001.

[5] H Koser, F Cros, MG Allen and JH Lang, "Magnetic Diffusion Modeling in Nonlinear Micro-Media: A Modified Finite-Difference Time-Domain Approach", International Conference on Modeling and Simulation of Microsystems, March 2003. To appear.

[6] H. Koser, "Development of Magnetic Induction Machines for Micro Turbo Machinery", PhD Thesis, EECS Department, MIT, June 2002.

[7] F. Cros, "Développement et test d'une micro-machine à induction magnétique ettechniques de micro-fabrication pour micro-composant électromagnétique" These doctorale francaise, Ecole doctorale de Toulouse, France, Septembre 2002.

[8] M. Xu, T. M. Liakopoulos, C. H. Ahn, S. H. Han, and H. J. Kim, "A microfabricated transformer for high-frequency power or signal conversion," *IEEE Trans. Magn.*, vol. 34, pp. 1369-1371, July 1998.

[9] J. Park, S. H. Han, and M.G. Allen, "Batch-fabricated microinductors with electroplated magnetically anisotropic and laminated alloy cores," *IEEE Trans. Magn.*, vol. 35, no. 5, pp.4291-4300, 1999.

[10] C. R. Sullivan and S. R. Sanders, "Microfabrication process for high-frequency power-conversion transformers," in *26th Annu. Power Electronics Specialists Conf.*, June 1995, pp. 658-664.

[11] J. Park, J. Y. Park, Y. Joung, and M. G. Allen, "Fabrication of high current and low profile micromachined inductor with laminated Ni/Fe core," *IEEE Trans. Component and packaging Technology*, submitted.